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A Technology Architecture for Accessing the Oceans of Icy Worlds

Tom Cwik[a]*, Wayne Zimmerman[a], Andrew Gray[a], Bill Nesmith[a], Raul Polit Casillas[a], Juergen Muller[a], Dave Bell[a], Scott Bryant[a], Arbi Karapetian[a], Richard Otis[a], Kevin Hand[a], Margarita Brandt[a], Kris Zacny[b], Anita Sengupta[c]

[a] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, United States,* cwik@jpl.nasa.gov
[b] *Honeybee Robotics, Pasadena CA, United States*
[c] *Hyperloop One, Los Angeles CA, United States*
* Corresponding Author

Abstract

The icy moon oceans beckon with ingredients that potentially may harbour extant life. Beginning with the Galileo and Cassini missions, measurements have revealed the presence of global oceans under the icy crust of several moons of Jupiter and Saturn. Among those moons, Europa and Enceladus have their ocean in contact with the rocky core, providing an environment similar to the conditions existing on the terrestrial sea-floor where life has developed at hydrothermal vents Accessing these oceans presents considerable difficulty due to a number of issues including the depth and composition of the icy crust, the time needed to travel through the crust, the power needed to propel a probe, communication of scientific and engineering data though the ice and back to Earth, entry and mobility in the ocean and autonomous operations for the life of the mission. A detailed trade space study was conducted to develop a technology architecture defining a system that would access an icy moon's ocean. To specifically bound the architecture, Jupiter's moon Europa was chosen as the target body though the work can apply to other bodies. The current understanding of the scientific properties of the ice crust and ocean was used to guide the development. A strawman scientific payload was devised to further develop a baseline set of requirements. Beginning with a launch and trajectory that can bring a system to Europa's orbit, a complete trade space was developed outlining the engineering systems needed to access the ocean. The architecture was divided into specific phases for i) deorbit, descent and landing, ii) surface operations, iii) ice descent and iv) ocean access. The technical maturity of each of sub-system for the phases was assessed for systems that could be developed to a maturity ready for a preliminary design in less than ten years. Integrated system parameters on power, communication capacity, and mass were developed to further define the overall system. To constrain the design, a total time in the ice, from the ice crust surface to accessing the ocean was limited to three years, and 15Km of ice was baselined with a temperature profile through the ice estimated from the scientific literature.

Keywords: ocean worlds, Cryobot, ice probe, Europa, Enceladus

1. Introduction

The icy moon oceans beckon with ingredients that potentially may harbour extant life. Beginning with the Galileo and Cassini missions, measurements have revealed the presence of global oceans under the icy crust of several moons of Jupiter and Saturn. Among those moons, Europa and Enceladus have their ocean in contact with the rocky core, providing an environment similar to the conditions existing on the terrestrial sea-floor where life has developed at hydrothermal vents [1-3]. Accessing these oceans presents considerable difficulty due to a number of issues including the depth and composition of the icy crust, the time needed to travel through the crust, the power needed to propel a probe, communication of scientific and engineering data though the ice and back to Earth, entry and mobility in the ocean and autonomous operations for the life of the mission. A detailed trade space study was conducted to develop a technology architecture defining a system that would access an icy moon's ocean. To specifically bound the architecture, Jupiter's moon Europa was chosen as the target body though the work can apply to other bodies.

2. Assumptions and Mission Phases

To begin the study, a series of assumptions were developed that would guide and inform the trade space development and inform technical decisions. The assumptions were naturally grouped into a set of notional mission phases to organize full lifecycle development of the Cryobot. A key parameter that drives a landed mission to an ocean world is the available mass at the surface of Europa. To bound the landed mass for the Cryobot system, mission design parameters from the Europa Lander project were used [1, 4]. This includes using the SLS launcher with the same dry mass as that mission, similar trajectory design to Jupiter and then to Europa, and a similar deorbit system. The Europa Lander concept baselines a skycrane descent and lander, motivated by the requirement of not disturbing the ice surface before science operations begin. Because of the science goal of travelling through the crust and reaching the ocean, this requirement was not enforced in the study. A fixed descent and lander system that would hold the Cryobot was notionally developed; the lander system would hold and release the Cryobot and be part of the communications link. As will be described below, communication electronics will not remain on the surface due to the radiation loading, though an antenna system that can resist the radiation loading would. The antenna under development for the Lander concept or a related system would be used [5]. The lander system was designed to provide the ability to land within 100m of a prescribed location, and this criterion was assumed in this study [6]. Surface data from the NASA Clipper mission is also assumed and is essential to characterize the Europan ice crust including potential landing sites [7]. Besides the lander system and communication antenna, the Europa Lander concept would also bring further scientific characterization of the crust, the engineering experience of landing to 100m accuracy, and operations in a cryo-ice environment.

Additional assumptions involve the environment the Cryobot must operate in. Upon touching the surface, the lander vehicle and Cryobot must operate in the Europan surface environment including the radiation field, vacuum and temperature. Initial operations must include entry of the Cryobot from vacuum into the approximately 100ºK ice with a complex and chaotic surface that may have a rich salt content [8] and uneven surface structure perhaps layered with desiccated salts. Once within the crust, a range of parameters of the ice environment are assumed. For this study we are assuming an ice crust thickness of 15km, a specific depth-temperature profile as described in [9], and a range of salt content that can impact transfer of heat from the Cryobot. The time necessary to descend the 15km depth is variable and highly dependent on a number of factors including the diameter and length of the Cryobot, the characteristic of the ice crust and the amount of thermal power available in the Cryobot, including the conversion of an amount of thermal energy to electrical energy to operate Cryobot systems. These factors will be used to predict the amount of time necessary to descend through the ice and be drivers for a trade analysis on Cryobot size and power to reduce the descent time to produce a system that can be engineered for flight.

To organize the Cryobot system capabilities, a set of mission phases are defined in Figure 1. The key functions of each phase are

- Landing: includes the deorbit, descent and landing systems that will bring the Cryobot to a specified Europan location.
- Surface: includes the functions of releasing the Cryobot into the ice, maintaining communication to and from the Cryobot as well as communications direct-to-Earth or to an orbiter relay. These systems must be able to operate in the radiation and thermal environment over the life time of the mission
- Ice Descent: includes the functions of descending through the entire crust thickness, transmit and receive communication from the surface, and carry the science instrumentation payload.
- Ocean Access and Mobility: includes detection and entry into the ocean at the ice-ocean interface, exploration of the ice-ocean interface as well as some depth and range of the ocean and maintain integrity of planetary protection.

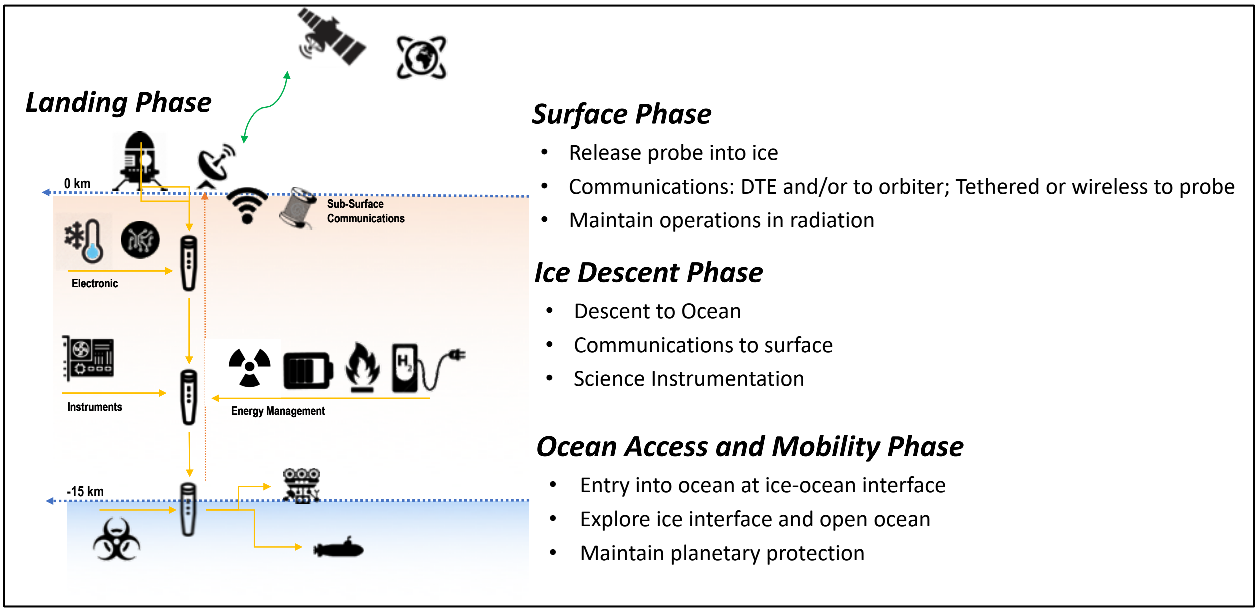

Figure 1: Cryobot mission phases used to organize the design.

The assumptions and mission phases were used to define a set of functional requirements for each Cryobot system. The majority of time in the study was spent developing each system that, with additional technology development, could meet the Cryobot functional requirements. Competing Cryobot system designs were developed. Computer-aided engineering design and analysis using a range of structural, electrical (e.g. communications, autonomy state diagrams), thermal and other tools were used to quantify the system design and allow decisions to be made. At each key decision point, maturity of the subsystems was characterized by their readiness and potential to be matured to a flight system over the ten-year time frame.

Additionally, a design principle to integrate redundant capabilities, as feasible, to mitigate unknown environmental risks was applied throughout the study. As will be outlined, this resulted in three methods for ice descent and two methods for communication. These are separate from using redundant components and sub-systems.

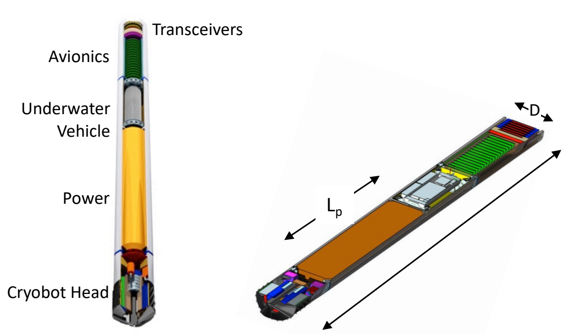

Figure 2: Notional schematic of Cryobot indicating key systems. The probe diameter is D, the length is L and the length of the section for the power system is L_P.

3. Key Systems for the Cryobot

The mission phases define an architecture where the functions of the key systems can be identified and their associated technology maturity assessed. A schematic of the Cryobot is shown in Figure 2.

It consists of a Cryobot head where the ice descent systems are located, followed by the power system, the underwater vehicle, a stack of avionic electronics boards indicated in green and then the communication transceivers. A thermal management system is integrated into the power system.

As will be described below, during the trade study, all systems were designed to find an optimal design given the initial range of constraints. The diameter of the Cryobot became fixed, while the length of the power system can take a few values dependent on the type of packaging of the radioisotope source. After the probe diameter, this length and the resulting available power is a key parameter impacting the time for descent though the crust. Figure 3 describes key subsystems for the mission phases and key decisions that were considered in producing an integrated system. The following is a summary of the key results.

3.1 Deorbit, Descent and Landing

The deorbit, descent and landing phase is driven by the requirement of precision landing, and without a self-imposed requirement of not disturbing the surface during landing. Precision landing rules out any ballistic hard landing or penetrator, reducing the trade space to

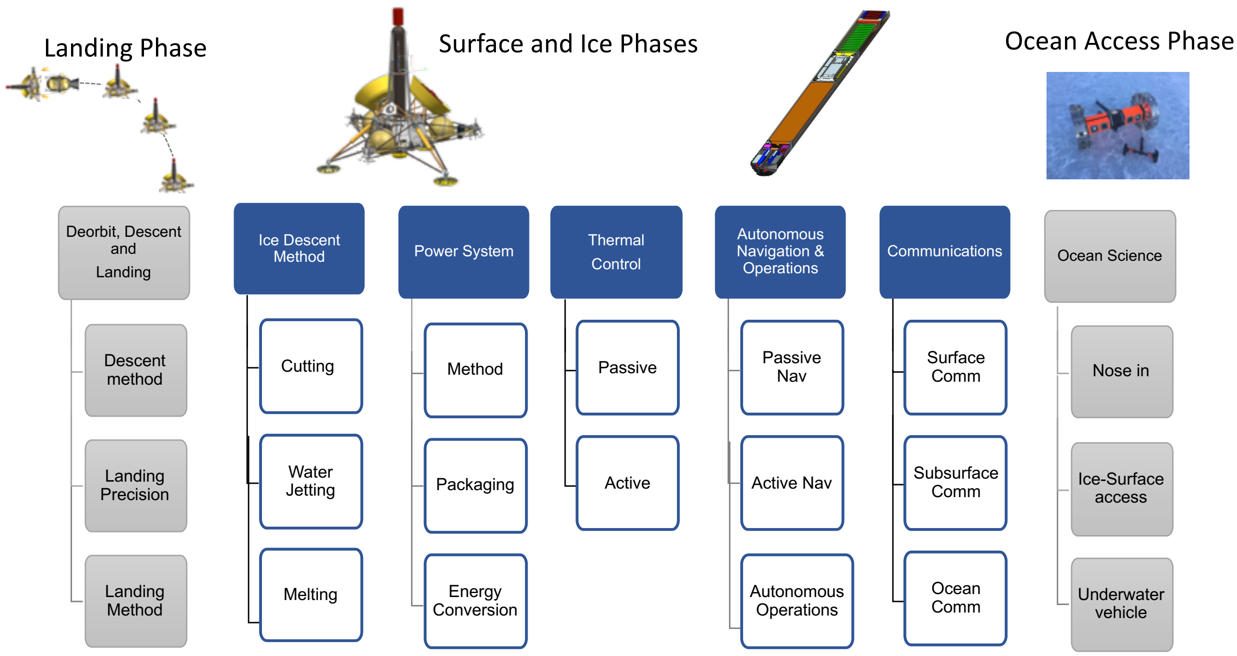

Figure 3: Key systems of the Cryobot mission and potential options for each system.

skycrane and propulsive landing systems. To optimize mass of the overall landed system, a notional design for a propulsive lander was created that could hold a Cryobot while maintaining stability during descent. Without the need to not disturb the ice surface, the skycrane, though demonstrated in Mars missions, is viable but was recognized to add mass and complexity. For the purpose of this study a notional propulsive landing system with legs that will level the Cryobot for entry into the crust was developed. The propulsion subsystem, including engines and tanks, was sized, and a set of avionics for the descent and landing phase was identified. A cap that would descend to the surface, aiding entry of the probe into the ice was also part of the lander vehicle. As described above, the key component that would be operational through the lifetime of Cryobot operation is the antenna for communications to Earth.

3.2 Ice Descent

Ice descent is driven by the requirements to descend in less than three years, maintain reliability of components for that time, operate in the ice environment that can potentially include salts, sediment layers and voids and handle potential stopping and stalling. Travel through the crust can be accomplished generally by the processes of melting or mechanical cutting. By melting the ice below the probe while maintaining a sheath of liquid around the length of the probe, the Cryobot will continuously fall, descending through the ice. Thermal energy raises the temperature of the ice to the melting point with the addition of the energy of latent heat then melting the ice. Through mechanical cutting, the ice can be excavated beneath the head, and if the chips are removed and a sheath of liquid is maintained along the length of the probe, the Cryobot will descend. Conduction of the heat into the ice crust will carry away energy, and a range of mechanical process will impact the descent [10, 11]. It can be expected that sediment layers may form below the Cryobot impeding travel, or voids and obstructions can be in the path of the probe. Fundamentally, the entire column of ice must be melted or removed through cutting for the Cryobot to reach the ocean. For the cylindrical probe envisioned, the area of the probe cross-section and the length of the probe are key parameters in the design.

The energy source is intimately coupled to the ice descent approach. Given the amount of energy and length of time needed to melt the column of ice, the decision tree quickly branched to a nuclear source. The power can be generated within the Cryobot, or by a generator at the surface where the power is transferred by a tether to the probe. During the trade space development, a surface generator was assessed to be outside the mass constraint, e.g. a nuclear fission system with appropriate shielding. The tethered system also requires the tether to withstand any shear movement especially within the top brittle layer of the ice crust. This tether would be a single point of failure when using a surface power system. As a result, the trade space reduced to carrying radioisotope power within the Cryobot to supply both thermal energy for melting and conversion of the heat to electrical energy to power the probe.

An additional approach for melting is the use of waterjets with warmed water resulted from thermal melt at the Cryobot head and recirculation. The use of waterjets also brings the ability to move any sedimentation that may develop beneath the head or to

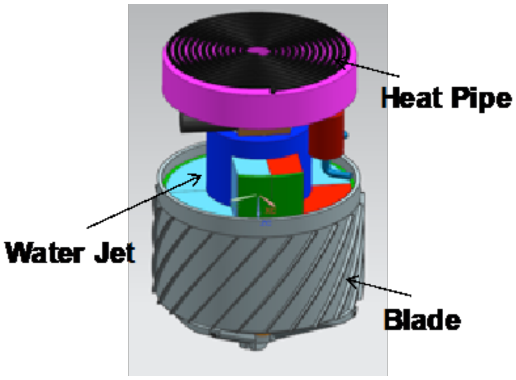

Figure 4: Schematic of Cryobot head combining elements of melting, mechanical cutting and water jetting.

melt and move material layers that may be in the ice. This approach was successfully demonstrated in [12]. Under the design philosophy of integrating redundant capabilities to mitigate the unknown environmental risks, a Cryobot head integrating thermal melting, mechanical cutting and water jetting was designed. Figure 4 shows the schematic of the head and subsystems. The mechanical blade must cut the ice and move the chips up past the head, being melted along the way. Work in blade size and the power necessary has been reported in [13, 14]. The water jet system consists of a series of pumps and valves to ingest the ice melt, warm the liquid and propel it through nozzles distributed around the head. The initial design consists of three nozzles distributed around the Cryobot head. Key considerations include maintaining optimal flow rates to melt ice ahead of the probe and eliminating any blockage from sediment.

The integrated design combining the three elements was assembled in CAD given known components or assumed extensions to available components. A key consideration is the location of the thermal power source or sources for the thermal melting component of the descent. The energy systems and thermal management systems are key in this piece of the design.

3.3 Power System and Thermal Management

Requirements for the power system are driven by the total amount of thermal energy available in the constrained volume to power the descent rates needed. The thermal management system is then required to move and manage the heat throughout the Cryobot. As described above, the Cryobot is powered by a radioisotope system based on a plutonium dioxide source. The dominate use of this thermal energy is for Cryobot descent, where the electrical energy that will be converted from the thermal source is secondary, needed for driving the motors in the water jets, cutting blade and the avionics and communication systems. This is contrary to most planetary systems where the electrical power is dominant and the thermal energy is treated mostly as waste heat. Currently available sources have a long developmental and operations history for planetary exploration [15, 16]. Thermal electric materials or other converters transform the thermal energy due to the decay of PuO_2 to electrical power. For the purposes of this study, a trade space was developed, based on the PuO2 material, with various form factors of a final packaged power source explored. The final form factor is dependent on a range of issues, dominated by safe use of the material. General purpose heat source blocks are one fundamental unit, with these blocks packaged into radioisotope thermoelectric generators of various types [16]. Designs of these generators are optimized for safe generation of electric power. As mentioned above, heat from the Cryobot energy source is predominantly used for descent rather than electrical power production; the ocean worlds Cryobot application can motivate alternate packaging of the PuO_2 material to provide greater volume specific power.

Accommodating the power system along with the Cryobot is central to the system trades considered. The volume and amount of thermal power available from the energy source will drive the overall design and the predicted time to descend through the crust. Designs based on individual general-purpose heat source blocks, the variants of the radioisotope thermoelectric generators and a potential new packaging approach are feasible. All systems require a fraction of the thermal power to be converted to electrical power for Cryobot operations but in the range of 10%, in-family with existing thermoelectric converters. This study examined packaging the general purpose heat source blocks as well as a potential new packaging of the PuO_2 material which may reduce the volume shown in Figure 2 for the power system [17, 18]. The fundamental change is in the length and the amount of thermal energy available in the power section. Packaging existing radioisotope systems that are larger in diameter were not considered in this study but are being examined elsewhere. Based on accommodating the descent systems in the Cryobot head, the electronics packages and the science package, a diameter of 23cm was arrived at as a feasible diameter. This diameter also allowed for thermoelectric generators around the radioisotope source thermal systems to transfer heat across the probe and the pressure vessel that holds the entire system.

Two key impacts of the volume and amount of thermal power on the Cryobot are the rate of descent through the crust and the feasibility of a thermal transfer and control system. As will be outlined in Section 5, the probe dimensions and amount of power directly impact the rate of descent and hence the overall time to reach the ocean. Depending on the volume specific power, a thermal management system that can transfer the correct portions of heat to the Cryobot head as well as across the cylindrical body needs to be engineered. Both passive thermal management systems and active heat pipe systems were considered in the study. A design which incorporates a heat pipe system into the pressure vessel walls of the Cryobot was also examined to reduce the probe diameter.

3.4 Electronics, Navigation and Strawman Science Payload

Requirements on the electronics and navigation system are dependent on the Cryobot operations as well the instrument needs in the science payload. To provide requirements for the Cryobot electronics, communications, volume and mass, a strawman science payload was developed. It is expected that this payload will approximate the functionality and accommodation of a Cryobot. The payload consisted of a set of miniaturized instruments and cameras and associated structure and electronics. It included radiation hard APS imagers that can be located at the probe wall as well as in an underwater vehicle, a gas chromatograph mass spectrometer, and a capillary electrophoresis extraction unit. A buoyant rover for under-ice exploration (BRUIE) was used as the strawman for the ocean access vehicle [19]. The existing BRUIE work was extended to decrease its diameter and volume, while maintaining its ability to function and explore within the ocean. A miniature version that fits the Cryobot was prototyped during the study.

The avionics was scoped to provide compute power to manage the autonomy systems, data collection and handling, fault protection, motor control, pump control, power conversion, and spacecraft telemetry. It was specified with block redundancy and a minimum lifetime for a mission lifetime of nine years. The electronics packaging form factor was 10cm x 10cm as part of the accommodation trade space and would require 1 MRAD total ionized dose operation as well as operation in the Cryobot thermal environment. Chassis and backplane structures were defined to guide the accommodations. The compute system that can provide the performance, fault tolerance, radiation protection, low-power operations and form factor was chosen to be the high performance space computer currently under development [20]. A motor controller with form factor and temperature operation was also identified [21].

Throughout the trade space, the Cryobot was constrained to operate autonomously with infrequent direction from operators. A set of autonomy functions was specifically developed for operations including lander levelling upon reaching the surface, hazard avoidance and navigation during descent, range and depth estimation, position knowledge and power usage and optimization (e.g. drill power). To accomplish these functions, a set of sensors were examined and included in the trade space to further bound the mass, volume and power. The sensors included an IMU and inclinometer, temperature, radiation and pressure sensors and forward-looking radar or acoustic sensors. A notional series of state space diagrams that captured the needed operations was developed to provide consistency with the software development and compute requirements.

3.5 Communications

The trade space development required the required data capacity from the strawman science payload and Cryobot telemetry be communicated to Earth. This required communication from the probe to the surface, through the ice, and then a link to Earth at rates that support the science instruments and housekeeping telemetry. Similarly, requirements for data from Earth to the Cryobot were placed on the system. The overall data capacity was dominated by the science payload. The decision space resulted in a series of transceiver pucks to link the data, puck-to-puck from the Cryobot to the surface, and a communications package for transmission to Earth. The communications electronics package would be placed a distance of approximately one-meter beneath the surface so as to be shielded from surface radiation. A tether from the communications electronics package to the lander at the surface and the communications antenna would complete the link. An additional approach would be to use a tether that would spool from the Cryobot, attached to the transceiver pucks, and provide a redundant and greatly increased data-rate communications path. As in the tether for the power source, the potential breakage due to ice shear or other movement would eliminate this means to communicate and would require further study.

The transceiver pucks follow from earlier work and are a hybrid design combining RF and acoustic transmission [22]. In the cold brittle ice, RF signal attenuation is small, increasing by an order of magnitude as the water content of the ice increases. Conversely, acoustic transmission has less attenuation in the warmer ice and penetrates ice-water interfaces such as liquid pockets in ice and slush. The pucks will be powered by radioisotope heater units with a thermoelectric converter and a set of transceiver electronics. The RF system was specified to operate at 100 MHz with a patch antenna at the top and bottom faces of the puck. The beam width for the patch at this frequency is broad, providing wide angular coverage. The transceiver acoustic element employs piezoelectric transducers integrated into the puck. The study indicated a range of 5-10 transceivers are needed to transmit the data capacities envisioned with fewer pucks needed in the cold brittle ice closer to the surface of the crust where attenuation is less and more as the Cryobot descends into the warmer ice.

4. A Concept of Operations

The study developed a notional concept of operations beginning with landing and extending until the Cryobot reaches the ocean and explores the ocean-ice interface. Shown in Figure 5 is the operational concept at landing.

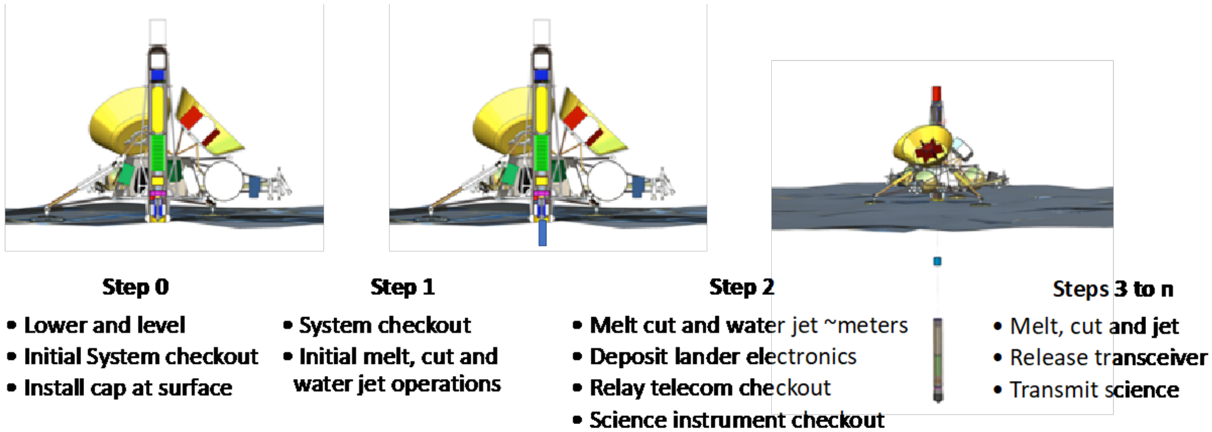

Figure 5: Notional operational concept at landing.

Based reconnaissance of earlier missions, a landing site will have been selected that allows the Cryobot to be placed within 100 m of a surface specified location. Upon landing, a leg levelling system allows vertical deployment of the probe. Borrowing from terrestrial drilling, a cap is lowered to the surface and allows pressure to build as the Cryobot is lowered within the cap to the ice. Initial thermal simulations indicated pressure will build with the cap as heat is transferred and the ice sublimates. The cutting blade is also expected to be essential during surface penetration. The purpose of Steps 1 and 2 is to lower the Cryobot a distance of a few meters into the ice to allow an electronics package to be deposited beneath the ice where it is protected from the radiation [23]. Once the electronics package is detached from the Cryobot, the probe continues to descend. A tether will be spooled from the electronics package back to the lander and the surface antenna.

During descent, the Cryobot will autonomously travel through the crust with limited ability to be controlled by a human in-the-loop. As described in Section 3.2, thermal transfer for melting, water jetting and mechanical cutting will drive descent. Since the radioisotope power source continually produces heat, the heat can be directed to different segments of the Cryobot as a means to slow or speed descent. The water jetting and mechanical cutting can be turned on and off, operating within a control system. Navigation data is found by a set of sensors that will be forward looking, sensing voids or any other disturbances in the ice. Steering the Cryobot off vertical is accomplished by a combination of differential heating or water jetting based on the sensed data [13, 24]. Release of the transceiver pucks at the appropriate distance is accomplished by monitoring the signal strength between the Cryobot and transceiver as the probe descends, and releasing one as necessary to maintain the communications channel. The thermal energy in the set of transceivers is part of the overall thermal management of the Cryobot – the heat at the top of the probe where the transceivers are located is available for maintaining the melt jacket along the length of the probe. There is not enough heat in each transceiver released into the ice to melt the ice about the puck and disturb its position. The Cryobot autonomously descends until the ocean-ice interface is sensed.

Once the Cryobot senses the ocean-ice interface the notional concept operations moves to a series of steps for the underwater vehicle to be deployed by tether into the water. An operation commences to anchor the back segment of the probe into the ice while the forward section detaches and continues to descend into the ocean. A tether of 10's of meters of length will allow the underwater vehicle to explore the ice-ocean interface, and the buoyant vehicle allows the exploration at the ice bottom. The instrument suite will sense and transit data back through the tether and through transmission by the transceivers to the surface where is relayed to earth.

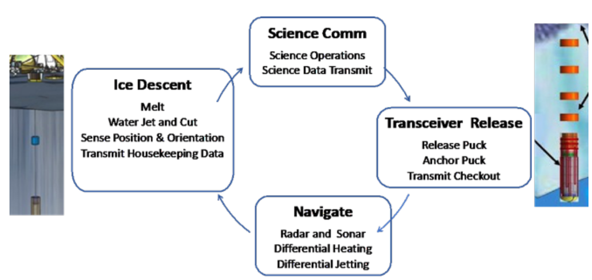

Figure 6: Notional operations during descent.

5. Predictive High-fidelity Ice Descent Models

During the study, it was recognized that central to closing a Cryobot design is a predictive and validated simulation of probe descent in the ice where there is a range of environmental uncertainties. The simulations must have enough fidelity to model the Cryobot descent driven by melting, water jetting and mechanical cutting. They must also be validated through experiments in laboratory chambers where the cryo-temperatures and pressures can be developed. The ice environment potentially will have a range of salt content that impacts transfer of heat for melting and conduction away from the probe. Additionally, though lab experiments can validate the models in perhaps meters to ten-meters of ice travel, longer travel can only be validated in glaciers and ice fields which differ from the cryo-ice and pressure properties of the Europan crust.

A set of three models have been defined, where each set has higher fidelity and a more complete model of the Cryobot physics and engineered systems. The set of models are meant to form an integrated Cryobot simulator that can be used to in developing experimental test facilities, forming a path to validation of the system and being used to design the Cryobot. As an analogue, the entry descent and landing design for Mars rovers is validated through rigorous simulation that achieves high

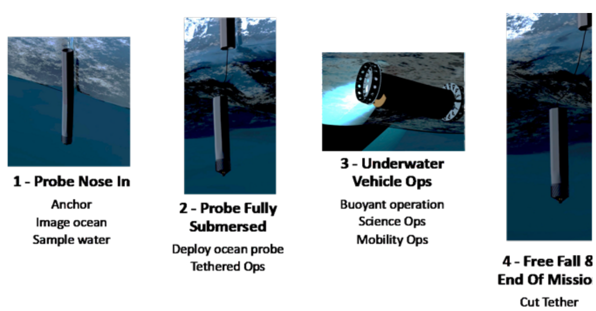

Figure 7: Notional operations at ocean-ice interface.

a priori confidence that the vehicle can descend through an uncertain atmosphere [25]. Because of the unknown environmental parameters, a framework that quantifies margins and uncertainties will be used in the simulations and associated validation experiments [26]. Descent by thermal melting and use of the waterjets can be modelled computationally, but the mechanical cutting does not lend itself to computation. For this descent process, experimental-based models can be constructed and built into the broader Cryobot simulator.

5.1 Analytical thermal probe model

Modelling the thermal characteristics of a melt-probe is accomplished using the Aamot model [10, 27]. The semi-analytic model provides a first-order calculation of descent rates as a function of an idealized probe with a

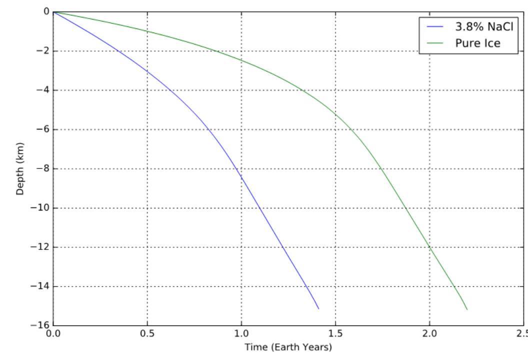

Figure 8: Time for descent through the crust.

given diameter, length and thermal power available for melting the ice at the base of the probe, and along its length, accounting for conductive losses. The temperature-depth model for the ice crust is used, as well as the dependence on the thermal conductivity and specific heat as a function of salt concentration [9, 28]. The Aamot model is used to quickly generate design curves for the Cryobot as the energy sources and dimensions are varied throughout the study [29]. Shown in Figure 8 is the plot for the Cryobot with dimensions 2.0m in length and 0.23m in diameter. The descent time in days is outlined as a function of depth. It is seen that the descent rate increases as the depth increases since the ice temperate increases form the assumed 100ºK at the surface to 273ºK at the ocean. Shown are plots for pure water ice and water mixed with a 3.8% NaCl salt concentration.

5.2 Commercial finite element model

The Aamot model provides a quick means to approximate the descent rate of a melt probe but is limited in a number of ways. To provide a more accurate approximation the commercial tools *Star CCM+*, *CFX*, and *Fluent* will be adapted to model both passive melting the and active waterjet melting. These tools model a static probe and the descent rate can be deduced from the receding liquid-solid water interface at the head of the probe after a melt layer is formed. The heat distribution can be better modelled throughout the surface of the Cryobot and connections to a thermal management system can be made. The models also allow a simulation of the waterjets by simulating the mass distribution, temperature and velocity of liquid exiting the Cryobot. Shown in Figure 9Figure 9 is a representative result of flow and melting from a waterjet at the head of the Cryobot.

5.3 *Generalized fluid flow with thermal transfer model*

The most accurate model would include high-fidelity two-phase physics of fluid flow coupled to heat transfer around the Cryobot in a time-varying calculation. A three-dimensional mesh-based calculation that includes descent in ice environments containing voids, sediment layers and cracks or other disturbances is being developed [30]. Due to the complexity of the physics and accurate modelling of the melt layer at the Cryobot surface, a high-performance computing environment is required. The model can be extended to include other effects such as close-contact melting and effects of gravity [11, 31]. It is expected that this model gives the most accurate simulations when validated against experiments.

6. Discussion

The results of the trade study have been presented, based on a set of assumptions, an architecture broken into phases of the lifecycle, a breakdown and decision space of the Cryobot systems, a notional concept of operations and the outline of high-performance predictive Cryobot simulator. Under the Atelier design approach, the CAD and analysis packages allow an integrated roll-up of the Cryobot properties. Shown in Table 1 is the notional current best estimate for the mass and power of the Cryobot as described above. The pieces column indicates the number of boars or modules integrated into that

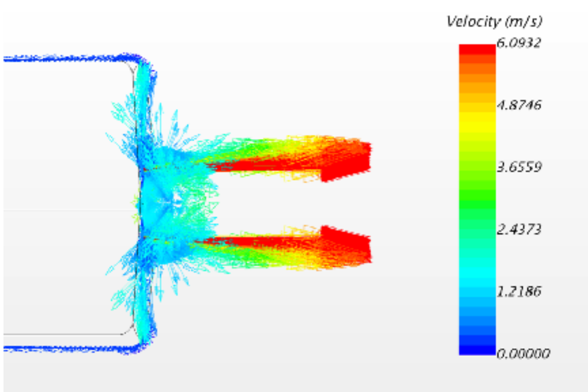

Figure 9: Simulations using Star CCM+ of waterjet.

system. Rollups for the total probe are shown in the top row. These estimates, and earlier numbers in during the trade study were key in forcing decisions along for the various systems and pieces.

Table 1: Notional current best estimate (CBE) mass and power

Cryobot Systems	Pieces	Mass (kg) CBE	Power (W) CBE
Total Probe	**1**	**211**	**597.6**
Navigation	12	4.6	11.4
Electronics	10	1.5	10.0
Power	7	33.3	4.0
Transceiver	10	5.6	30.0
Cutting and Water Jetting	1	16.0	400.0.
Underwater Vehicle	4	26.7	27.2
Structure	1	112.0	5.0
Thermal Management	1	11.2	110.0

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